

# Interaction-controlled transport of an ultracold Fermi gas

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We explore the transport properties of an interacting Fermi gas in a three-dimensional optical lattice. The center of mass dynamics of the atoms after a sudden displacement of the trap minimum is monitored for different interaction strengths and lattice fillings. With increasingly strong attractive interactions the weakly damped oscillation, observed for the non-interacting case, turns into a slow relaxational drift. Tuning the interaction strength during the evolution allows us to dynamically control the transport behavior. Strong attraction between the atoms leads to the formation of local pairs with a reduced tunneling rate. The interpretation in terms of pair formation is supported by a measurement of the number of doubly occupied lattice sites. This quantity also allows us to determine the temperature of the non-interacting gas in the lattice to be as low as  $(27 \pm 2)\%$  of the Fermi temperature.

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The study of conductivity in solids has led to the discovery of fundamental phenomena in condensed matter physics and to a wealth of knowledge on electronic phases. Intriguing quantum many-body phenomena such as superconductivity and the quantum Hall effect manifest themselves in their characteristic electronic transport properties. Moreover, the ability to manipulate conductivity has found numerous applications in technology, most prominently in semiconductors, where transport is controlled by electric biasing. Other ways to modify the conductivity in a material include adjusting temperature, pressure or magnetic field.

A gas of ultracold fermionic atoms exposed to the potential of an optical lattice offers a new approach to study and control transport while providing a direct link to fundamental models in condensed matter physics. A periodic potential of simple cubic symmetry is generated by three mutually perpendicular laser standing waves reproducing the potential experienced by electrons in the crystal structure of a solid. Prepared in two different spin states, fermionic atoms mimic spin-up and spin-down electrons. A unique feature of the atomic system is that the strength of the collisional interaction between the two components can be directly tuned using a Feshbach resonance [1, 2]. While this property has been used to study fermionic superfluidity in the strongly interacting regime (e.g. [3, 4]), it has so far not been applied to investigate transport phenomena in optical lattices. In previous experiments the transport of non-interacting fermionic atoms and the effect of a bosonic admixture mediating interactions were studied in one-dimensional optical lattices [5, 6, 7]. Furthermore, the dynamics of Bose gases in a three-dimensional optical lattice was investigated experimentally and theoretically [8, 9, 10].

In this letter we study the transport properties of a two-component <sup>40</sup>K cloud trapped inside a three-

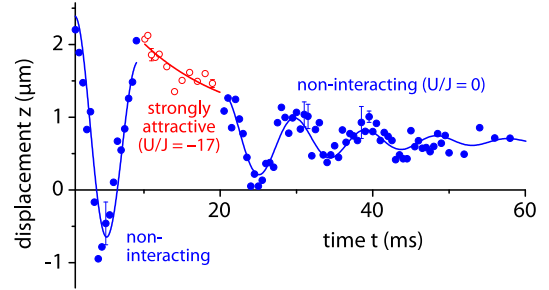


FIG. 1: (Color online) Dynamic control of transport by tuning the collisional interaction. The graph shows the center of mass motion of a two-component Fermi gas of  $(2.9 \pm 0.3) \times 10^4$  atoms in a lattice of  $5 E_R$  depth. At  $t = 0$ , the equilibrium position of the underlying harmonic trap is displaced vertically. After 9 ms of evolution without interaction ( $\bullet$ ), the magnetic field is changed linearly in 1 ms so that the interaction is strongly attractive ( $\circ$ ) for 10 ms. Then the magnetic field is changed to its original value again within 0.5 ms ( $\bullet$ ). The two non-interacting cases  $\bullet$  are each fit by a damped cosine and an offset, while the evolution with attractive interaction  $\circ$  is fit by an exponential decay and an offset. Error bars denote the standard deviation of at least 4 measurements.

dimensional optical lattice with underlying harmonic confinement. We monitor the center of mass motion of the atomic cloud after a sudden displacement of the trap minimum. The regimes of vanishing, weakly attractive and strongly attractive interactions are accessed by exploiting a Feshbach resonance to tune the scattering length for low energy collisions between the two atomic components. The atom number is adjusted so that at the trap center the lowest energy band is either filled or half-filled. For these parameters the system can be regarded as a realization of the attractive single-band Fermi-Hubbard model [11] with additional harmonic confinement. A Mott insulating phase of pairs as discussed

in the context of the multi-band Hubbard model [4, 12] is not expected.

The strong influence of the interactions on the transport is illustrated in Fig. 1. An atomic cloud is prepared in the optical lattice at half filling and brought into non-equilibrium by displacing the trap minimum. The initially non-interacting cloud performs a weakly damped oscillatory motion in the confining potential. By temporarily switching on the attractive interaction, a controlled interruption of this oscillation is achieved.

Our experimental setup that is used to produce quantum degenerate Fermi gases is described in detail in previous work [13]. In brief, we prepare a cloud of  $^{40}\text{K}$  atoms in an equal mixture of the hyperfine substates  $|F = 9/2, m_F = -9/2\rangle$  and  $|F = 9/2, m_F = -7/2\rangle$  in a crossed-beam optical dipole trap operating at a wavelength of 826 nm. After evaporative cooling we obtain  $4 \times 10^4$  ( $3 \times 10^5$ ) atoms at temperatures below  $T/T_F = 0.20$  (0.25) in the dipole trap with final trapping frequencies of  $(\omega_x, \omega_y, \omega_z) = 2\pi \times (35, 23, 120)$  Hz, where  $T_F$  is the Fermi temperature. Next, the degenerate Fermi gas is subjected to the additional periodic potential of a three-dimensional optical lattice with a depth of  $5 E_R$ . The recoil energy is given by  $E_R = \hbar^2/(2m\lambda^2)$ , with  $\hbar$  being the Planck constant,  $m$  the atomic mass and  $\lambda = 1064$  nm the wavelength of the lattice beams. The lattice is formed by three retro-reflected laser beams with circular profiles having  $1/e^2$  radii along the  $(x, y, z)$ -directions of  $(160, 180, 160)$   $\mu\text{m}$  at the positions of the atoms and a mutual frequency difference of several 10 MHz. To load the atoms into the lowest Bloch band of the optical lattice we increase the intensity of the lattice beams using a spline ramp with a duration of 100 ms at a scattering length of  $a = 50 a_0$ , where  $a_0$  is the Bohr radius.

The gas is brought into a non-equilibrium position by increasing the beam intensities of the underlying dipole trap, which shifts the trap minimum by up to  $2.5 \mu\text{m}$  in the vertical  $z$ -direction. Since this displacement is smaller than our imaging resolution, we map the center of mass position of the atomic cloud to momentum space. For this purpose we switch off the optical lattice and let the cloud oscillate in the remaining harmonic dipole trap for a quarter period [8]. After free expansion, we obtain the momentum distribution of the cloud from absorption imaging, determine the center of mass momentum using a Gaussian fit and infer the original displacement  $z$  of the cloud in the trap. Oscillations of the cloud size are not observed since the horizontal and vertical trapping frequencies are only increased by about 4% and 12%, respectively. Also, Bloch oscillations can be neglected for our small displacement since even for large fillings only few atoms gain sufficient energy to reach the band edge [14]. The energy deposited in the system by the trap displacement is estimated to increase the temperature in the lattice by an amount of  $0.05 T_F$ .

Variation of the magnetic bias field in the vicinity of

the Feshbach resonance at 202.1 G [2] allows us to tune the collisional interaction between the two components of the Fermi gas. Prior to the displacement of the trap the magnetic field is gradually ramped to final values between 210 G and 202.95 G within 50 ms, yielding an  $s$ -wave scattering length ranging from 0 to  $-1500 a_0$ . Using the description of a Hubbard model for cold atoms [15, 16], this corresponds to an effective interaction strength  $U/J$  between 0 and  $-24$ . Here  $U$  denotes the on-site interaction energy of two atoms in a different spin state, and  $J$  is the matrix element for nearest-neighbor tunneling, which has a value of  $J \approx \hbar \times 290$  Hz for our lattice depth.

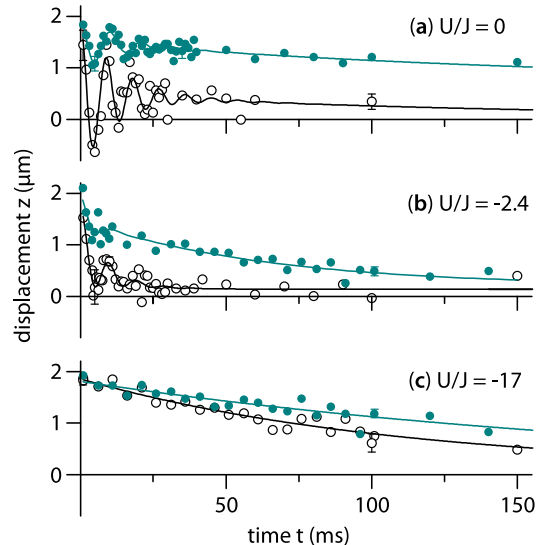


FIG. 2: (Color online) Evolution of the center of mass position for different interaction strengths and fillings. The circles  $\circ$  ( $\bullet$ ) denote samples in the half filled (band insulating) regime. For each data point the position of the cloud with and without displacement was compared to eliminate long term drifts. The error bars denote the standard deviation of at least 4 measurements.

The results of transport measurements for three interaction strengths and two different fillings are shown in Fig. 2. We fit the function  $z(t) = z_{\text{osc}} \cos(2\pi f t) \exp(-\beta t) + z_{\text{exp}} \exp(-\Gamma t) + z_0$  to the data. For the half filled case,  $(3.6 \pm 0.4) \times 10^4$  atoms are prepared corresponding to  $0.46 \pm 0.05$  atoms per lattice site and spin state at the center of a non-interacting cloud [19]. In the case of high filling, the samples contain  $(2.7 \pm 0.3) \times 10^5$  atoms and form a large band insulating core. The filling factor of the Bloch band is position-dependent due to the inhomogeneous density profile of the trapped gas. In the following, we will discuss the cases of zero, moderate and strong interaction.

In the non-interacting case with half filling we observe damped dipole oscillations (Fig. 2(a)  $\circ$ ). This damping of the center of mass motion can be attributed to the fact that the fermions in different quasi-momentum states possess different effective masses, resulting in a spectrum

of oscillation frequencies. Furthermore, the total trapping potential is slightly anharmonic, which causes a dephasing also observed in the pure dipole trap. The system with high filling (Fig. 2(a)●) is characterized by a very slow relaxation towards the equilibrium position: The band insulating core suppresses center of mass motion and a large number of atoms occupy localized states [7, 17, 18]. These single particle eigenstates exist at a distance  $z_{\text{loc}}$  from the center of the trap where the potential energy due to the harmonic confinement is larger than the bandwidth, i.e.  $m\omega_z^2 z_{\text{loc}}^2/2 > 4J$ . Consequently, the motion through the center is energetically prohibited, however, the atoms can still oscillate within the outer regions of the cloud. Even in the half filled case a small fraction of atoms is localized, which explains the small offset observed in the center of mass position after the decay of the oscillations (Fig. 2(a)○).

For moderate attractive interaction and half filling, the damping of the dipole oscillations becomes more pronounced (Fig. 2(b)○). The damping rate  $\beta$  increases from  $(80 \pm 17)$  Hz in the non-interacting case to  $(140 \pm 37)$  Hz at  $U/J = -2.4$ . As the interaction strength is increased beyond  $U/J < -3.5$ , the oscillations vanish entirely. The sample with high filling (Fig. 2(b)●) relaxes faster towards equilibrium than in the non-interacting case, which can be attributed to umklapp processes [20].

In the strongly interacting case, a very slow relaxation is observed for both fillings [Fig. 2(c)]. The transport in this regime is governed by the dynamics of local fermionic pairs. In the limit of low atomic densities bound pairs form for  $U/J < -7.9$  [11, 21, 22]. These pairs tunnel to adjacent sites via a second order process with an amplitude  $J_{\text{eff}} = 2J^2/U$ . This effective tunneling is obtained by considering a ground state where all atoms form pairs and by treating the tunneling term proportional to  $J$  as a perturbation in the Hubbard Hamiltonian [11]. Accordingly, the tunneling rate of pairs is reduced with increasing interaction as compared to bare atoms. Besides, the energy offset between neighboring sites due to the harmonic confinement reduces the tunneling probability. For these reasons we expect the relaxation time to become longer for stronger interactions. This is supported by the data in Fig. 3, which shows a clear decrease of the relaxation rate  $\Gamma$  for growing attractive interaction. The data is well fit by the empirical power law  $\Gamma/J \propto (U/J)^{-1.61}$ . A quantitative understanding of this behaviour is challenging due to the coexistence of bare atoms and local pairs which act as hardcore bosons in the lattice.

Further insight into the physics of local pairs is gained by probing the double occupancy in the lattice for various interaction strengths without displacing the trap. For this purpose, we prepare the system at half filling, as before, and set the desired interaction within 50 ms by changing the value of the magnetic field. Then the lattice depth is abruptly increased from  $5 E_R$  to  $30 E_R$  in order to suppress further tunnelling. By subsequently ramping

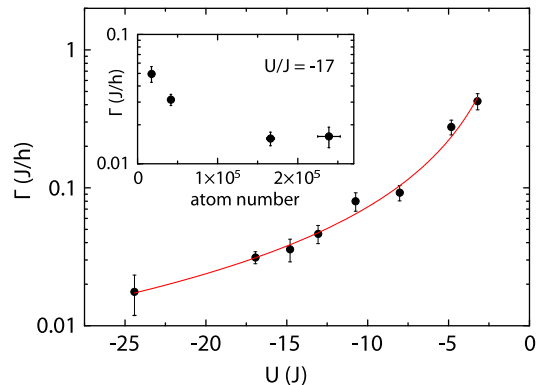


FIG. 3: Relaxation rate  $\Gamma$  as a function of interaction strength. The data points and error bars are fit results to center of mass evolutions of  $(3.8 \pm 0.4) \times 10^4$  atoms. The empirical power law  $\hbar\Gamma = CJ(J/U)^\nu$  with  $\nu = 1.61 \pm 0.03$  and  $C = 2.95 \pm 0.17$  fits the data well. The inset shows the dependence of the relaxation rate on the atom number.

the magnetic field from 203.26 G to 201.23 G within 5 ms, weakly bound Feshbach molecules are formed on those sites which are doubly occupied [21]. We determine the number of atoms remaining after the molecule formation and compare it with the atom number which is obtained after dissociation of the molecules by applying the inverse magnetic field ramp. This yields the molecular fraction displayed in Fig. 4, showing a strong dependence on the interaction strength: While for the non-interacting system the detected fraction is 18%, it increases up to 60% for strongly attractive interactions.

For the non-interacting gas the double occupancy in the lattice is solely determined by the number of trapped atoms and their temperature [19, 21, 23]. The detected fraction of 18% is consistent with the temperature in the lattice of  $(0.27 \pm 0.02) T_F$ , which we determined in a separate measurement with  $2.7 \times 10^5$  atoms yielding a molecular fraction of  $(45.7 \pm 2.4)\%$ . This temperature, even though measured in an ideal gas, suggests that the gas remains above the critical temperature for superfluidity [11, 24, 25] also for strong interactions. Numerical calculations for an homogeneous interacting system show a considerable temperature dependence of the double occupancy [24]. We therefore expect that the temperature of the interacting gas can be deduced from the measured double occupancy.

The increase of the molecular fraction with rising attractive interactions provides strong evidence for the formation of local pairs. In accordance with numerical calculations for the attractive Hubbard model at finite temperature [24, 25] the number of doubly occupied sites increases already for weak attraction, i.e. in a regime where no bound state exists in the two-body problem ( $U/J > -7.9$ ). Pair formation in the many-body regime is expected to start at a value of  $U/J \approx -2$  [25].

For strong attractive interactions, i.e.  $U/J < -7.9$ ,

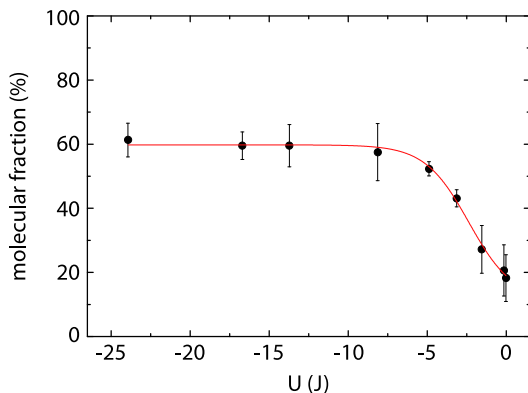


FIG. 4: The fraction of molecules formed in the optical lattice increases with attractive interaction, demonstrating a higher number of doubly occupied lattice sites. Error bars denote the statistical errors of at least 4 measurements. The line serves as a guide to the eye.

the number of doubly occupied sites saturates. This is in accordance with the fact that the pairs are well localized on single lattice sites and can be regarded as hard-core bosons. An increase in molecular fraction due to an attraction-induced shrinking of the cloud, which would result in a higher average density, is not substantiated by the following measurements: When tuning the interaction strengths we could not detect a change in the size of the trapped atom cloud with our measurement accuracy of 10%. Furthermore, the same increase in molecular fraction is found if the attractive interaction is turned on within only one tunneling time. This demonstrates that we observe local pairing rather than a redistribution of the trapped atoms on a larger scale.

In conclusion, we have found that the transport of an attractively interacting Fermi gas in a 3D optical lattice is strongly influenced by the formation of local pairs. In the future, studying the oscillation frequency below the superfluid transition temperature could serve to characterize the BCS-BEC crossover [26]. Extending our studies to the repulsive Fermi-Hubbard model may provide a tool to identify quantum phases such as the fermionic Mott insulator [27].

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